

# SOLAR CORONAL OBSERVATIONS AND FORMATION OF THE He II 304 Å LINE

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Received 1992 July 28; accepted 1992 September 24

## ABSTRACT

Although a large body of recent work supports the formation of the He II 304 Å resonance line ( $1s^2S_{1/2}-2p^2P_{1/2, 3/2}^o$ ) by collisional excitation in the quiet Sun, the formation mechanism is less clear in strong coronal active regions and flares. The 1989 May 5 flight of the Goddard Solar Extreme Ultraviolet Rocket Telescope and Spectrograph (SERTS-3) provided a data set that is well suited to addressing this question. This paper develops a method of assessment of the line formation mechanism that is based on simple non-LTE theory and is applied to these data. The results support the conclusion of other authors that the 304 Å line is formed by collisional excitation in the quiet Sun, but that photoionization-recombination (p-r) may play a significant role in coronal active regions, and that p-r is important, and may even be predominant, in many flares.

*Subject headings:* atomic processes — Sun: corona — Sun: UV radiation

## 1. INTRODUCTION

There is still uncertainty over the formation of the He II 304 Å resonance line in some solar features. While recent work by a number of investigators supports collisional excitation in the quiet Sun network, the situation in active regions and flares is less clear. For example, Athay (1988) argues for collisional excitation in the network, while Zirin (1988) reviews the arguments favoring photoionization-recombination (p-r) over much of the Sun.

One reason for the difficulty of obtaining a definitive result in active regions is the lack of a data set that provides the required spatial and spectral resolution in both the 304 Å line and also in those coronal lines from which one can estimate the local radiation field that contributes to the p-r process, especially for wavelengths below the He II ionization limit at 228 Å. Observations from the SERTS-3 flight of 1989 May 5, (Thomas, Neupert, & Thompson 1993; Thompson et al. 1992) can be readily adapted to this analysis. The spatial resolution in images obtained with the broad part of the SERTS entrance slit, and also along the narrow part of the slit used to obtain spectra is on the order of 5"–30", depending on the solar contrast. This is not as small as some of the features of interest, but it is adequate for establishing systematic differences between different types of emitting regions. The corresponding spectral resolution of the narrow slit spectra is between 50 and 70 mÅ, which is adequate for obtaining values for the absolute intensities of several strong coronal lines. The SERTS-3 spectrum therefore provides the basis for estimating the flux of coronal radiation in the formation region of the 304 Å line.

A complete description of the SERTS-3 instrument and flight, with a brief overview of the results of the flight, appears in Neupert et al. (1992b).

## 2. DESCRIPTION OF THE RELEVANT DATA

During the flight of 1989 May 5, spectroheliogram images and spectra were obtained for both a quiet portion of the solar

atmosphere and for an active region (NOAA AR 5464) near the west limb of the Sun (see Fig. 6a in Neupert et al. 1992b). The first two exposures, of 97 and 20 s each, were taken with the AR located in the western wide lobe of the hourglass-shaped slit, as illustrated in the above referenced figure. The final exposure was of 256 s, with the last 246 s occurring in the second pointing position (Fig. 6b in Neupert et al. 1992b).

Figure 1 (Plate 15) shows the spatial intensity distribution of the He II 304 Å emission and of the four coronal lines used in this analysis over the two solar areas for which we have obtained calibrated intensities from slit spectra. On the left-hand side of Figure 1 appear images of the relatively quiet Sun with the wide lobe farthest from the west limb in pointing position 2, taken with a total exposure time of 256 s. On the right-hand side of Figure 1 appear images of AR 5464 with the wide lobe closest to the solar west limb in pointing position 1, taken with an exposure time of 97 s. The location of the narrow slit used to obtain corresponding quiet Sun and AR spectra is shown on the two 304 Å images. The portion of the AR identified as intense AR along the slit is that (nonflaring) portion over which the strong Fe XVI lines are most intense, and for which the Fe XVI intensity distribution along the slit suggests loop structures, although potential magnetic field computations performed over most of the AR do not establish the presence of loops in the intense AR region unambiguously (Neupert et al. 1992a). The subflare spectra were averaged over the portion of the slit illustrated in Figure 1. Exposure times for these spectra are 117 s for the quiet Sun spectra (sum of first two exposures) and 256 s for the active region spectra.

Table 1 lists the absolute photon intensities at Earth, determined from SERTS-3, and the corresponding energy fluxes at the Sun's surface, of the strong coronal lines used in this analysis, averaged over those portions of the narrow slit illustrated in Figure 1. The values are given for the four regions already identified: quiet Sun, active region, intense AR, and subflare.

TABLE 1  
DATA<sup>a</sup>

ION	log <i>T</i>	$\lambda$ (Å)	INTENSITY (cm <sup>-2</sup> s <sup>-1</sup> arcsec <sup>-2</sup> ) (FLUXES [ergs cm <sup>-2</sup> s <sup>-1</sup> ])			
			Quiet Sun	AR Average	Intense AR	Subflare
Mg IX .....	6.0	368.07	53 (3.82E+2)	603 (4.35E+3)	676 (4.88E+3)	943 (6.80E+3)
Fe XV .....	6.3	284.16	344 (3.21E+3)	2993 (2.80E+4)	4549 (4.25E+4)	3270 (3.06E+4)
Fe XVI .....	6.4	335.40	156 (1.24E+3)	4850 (3.84E+4)	7364 (5.83E+4)	10630 (8.42E+4)
Fe XVI .....	6.4	360.75	70 (5.15E+2)	2171 (1.60E+4)	3417 (2.51E+4)	4653 (3.42E+4)

<sup>a</sup> Absolute integrated intensities at Earth for four strong coronal lines observed on SERTS-3 flight of 1989 May 5 in photons cm<sup>-2</sup> s<sup>-1</sup> arcsec<sup>-2</sup> (Thomas et al. 1993), converted into corresponding energy fluxes at the Sun's surface in ergs cm<sup>-2</sup> s<sup>-1</sup>. The quiet Sun values were averaged over the narrow slit in pointing position 1, and the other values were obtained over the portions of the slit in pointing position 2 that are illustrated in Figure 1.

Finally, in order to provide an independent check on our assessment of the 304 Å formation mechanism in a small flare that occurred in AR 5464 during the SERTS-3 flight, we estimated the XUV flux in the spectral range 1–228 Å for this flare from available *GOES* measurements of the solar flux for wavelength bands 0.5–4 and 1.0–8 Å (Solar Geophysical Data, 1989), and obtained a total power from the flare of  $3.8 \times 10^{25}$  ergs s<sup>-1</sup>. This value results from applying the method developed by Thomas, Starr, & Crannell (1985) to obtain a flare temperature and an emission measure for the radiation from the ratio of the flare fluxes (with background removed) in the above *GOES* bands, then using the computed dependence of the quantity  $P/N_e^2$  on the flare temperature from Kato (1976) to evaluate the product  $P/N_e^2$  times emission measure, which yields the power  $P$  emitted over the wavelength range desired (we actually used 1–200 Å, which to two significant figures gives the same result for our flare temperature as 1–250 Å), including contributions from predicted bremsstrahlung and recombination continua as well as from the XUV lines. We then estimated the flare flux for the 1–228 Å band by measuring the area in the SERTS active region image taken in the Fe XVI 335 Å line that brightened during the flare, and dividing the total power by this area. For a measured range of flaring areas of  $5\text{--}10 \times 10^{18}$  cm<sup>-2</sup> on the Sun, the corresponding range of flare flux in the 1–228 Å band incident on the transition region is estimated to be  $(3.8\text{--}7.6) \times 10^6$  ergs cm<sup>-2</sup> s<sup>-1</sup>.

### 3. ASSESSMENT OF THE He 304 Å LINE FORMATION MECHANISM

It is easy to show that, assuming complete redistribution, the source function for a line  $S_\nu$  can be written in the form

$$S_{\nu(U,L)} = \frac{\int J_\nu \Phi_\nu dv + \epsilon B_\nu(T_e) + \eta B^*}{1 + \epsilon + \eta}, \quad (1)$$

where the subscripts  $U$  and  $L$  refer to upper and lower levels of the line, and all other quantities have their usual definitions. Here, the term  $\epsilon B_\nu(T_e)$  measures the relative rate of collisional excitations in the line, and the term  $\eta B^*$  measures the relative rate of indirect processes that will populate the upper level of the line transition. For this reason these two terms are called source terms. Equation (1) was first derived by Thomas (1957).

The approach taken here is to evaluate these source terms for the 304 Å line. A simple first approximation for the source function for the He II ion is that of two bound levels and the

continuum. This approximation can be used to elucidate trends in the excitation mechanisms from the quiet Sun to active regions and flares. In this approximation, the ratio of the collisional source term  $\epsilon B_\nu(T_e)$  to the photoionization-recombination source term  $\eta B^*$  becomes particularly simple. If we call this ratio  $R$ , it is easy to show that, subject to reasonable approximations based on atomic rate coefficients, and following the general procedure outlined in Jefferies (1968),

$$R = 4.73 \times 10^{-11} N_e T_e^{-3/2} \frac{Y_{L\kappa}}{X_{LU}} \exp(Y_{L\kappa} - X_{LU}), \quad (2)$$

where  $X_{LU} = \chi_{LU}/kT_e$  and  $Y_{L\kappa} = \chi_{L\kappa}/kT_e$ ,  $\chi_{LU}$  is the excitation potential for the 304 Å line,  $\chi_{L\kappa}$  is the ionization potential of He II, and  $T_e$  is the Planckian radiation temperature that yields the energy density of the coronal radiation field for all wavelengths below the He II ionization limit of 228 Å. A radiative Gaunt factor of unity is assumed in the expression for photoionization in deriving expression (2), and the rate of collisional excitation is taken from van Regemorter (1962). The value of the radiative Gaunt factor was actually computed for a number of far-UV energies by Bhatia (1992) who used the latest atomic data, resulting in a value at the He II ionization limit of 0.8, increasing slowly toward higher energies with a nearly constant slope of  $0.004 \text{ Å}^{-1}$ . Since the quantity  $R$  in equation (2) varies inversely with a constant radiative Gaunt factor, the variation over the range 1–228 Å should produce less than a factor of 2 change in the value of  $R$ . Recent work on electron collisional excitation of ionized helium reveals a factor of 2 discrepancy between current theoretical and experimental cross sections for the (1, 2) transition that populates the upper level of the 304 Å line (Aggarwal et al. 1991). The values of van Regemorter lie within this range. If we assume that the correct value lies within this range, the use of the van Regemorter cross section will introduce at most a factor of 2 error into the value of  $R$ , which varies directly as the collision rate.

To obtain values of  $T_e$  from the SERTS-3 data, we make the following assumption:

1. The mean coronal flux from the whole Sun short of 228 Å can be obtained from the tables of Heroux & Hinteregger (1978), summarized here in Table 2.

2. The coronal flux below 228 Å corresponding to the reported Chapman & Neupert (1974) fluxes in the coronal lines summarized in Table 3 is assumed equal to the mean coronal flux in assumption (1) times the ratio of the measured fluxes in the approximately overlapping wavelength ranges 140–230 Å.

TABLE 2  
SOLAR FLUX AT EARTH<sup>a</sup>

Wavelength Range (Å)	Flux at Earth (ergs cm <sup>-2</sup> s <sup>-1</sup> )
1–10 .....	0.002
10–20 .....	0.002
20–30 .....	0.006
30–40 .....	0.050
40–50 .....	0.042
50–60 .....	0.020
60–70 .....	0.021
70–80 .....	0.019
80–90 .....	0.023
90–100 .....	0.020
100–110 .....	0.009
110–120 .....	0.003
120–130 .....	0.002
130–140 .....	0.001
140–150 .....	0.008
150–160 .....	0.011
160–170 .....	0.014
170–180 .....	0.089
180–190 .....	0.085
190–200 .....	0.062
200–210 .....	0.029
210–220 .....	0.024
220–230 .....	0.024

<sup>a</sup> From Heroux & Hinteregger 1978.  
These are essentially quiet Sun values.

3. The fluxes in the four strong coronal lines in Table 3 can be used, along with the Chapman & Neupert values of these fluxes, to estimate the local coronal flux short of 228 Å, by assuming that the fluxes in these lines are proportional to the coronal flux below 228 Å. The local estimated coronal flux below 228 Å can then be used to compute the local radiation temperature  $T_r$  that appears in equation (2) by the method described below, for each strong coronal line in Table 3 in each region observed along the narrow slit.

Derivation of a simple expression for the temperature  $T_r$  as a function of the flux  $F_r$  of coronal radiation short of 228 Å is straightforward. We start with the relation

$$F_r = 2\pi J_r = 2\pi \int_{\nu_{Lk}}^{\infty} B_{\nu}(T_r) d\nu, \quad (3)$$

and make use of  $h\nu \gg kT_r$ , a condition that is easily met over

TABLE 3  
OSO-3 MEAN CORONAL LINE ENERGY FLUXES<sup>a</sup>

Ion	log $T$	$\lambda$ (Å)	Mean Flux at Earth (ergs cm <sup>-2</sup> s <sup>-1</sup> )	Mean Flux at Sun (ergs cm <sup>-2</sup> s <sup>-1</sup> )
Mg ix .....	6.0	368.07	0.053	$2.44 \times 10^3$
Fe xv .....	6.3	284.16	0.124	$5.72 \times 10^3$
Fe xvi .....	6.4	335.40	0.063	$2.90 \times 10^3$
Fe xvi .....	6.4	361.75	0.026	$1.19 \times 10^3$

<sup>a</sup> From Chapman & Neupert 1974 for the same four lines appearing in Table 1.

the full range of conditions for this problem, to get

$$F_r \simeq 2\pi \int_{\nu_{Lk}}^{\infty} \frac{2h\nu^3}{c^2} \exp(-h\nu/kT_r) d\nu, \quad (4)$$

which, to excellent approximation, becomes

$$F_r \simeq \frac{4\pi k}{c^2} \nu_{Lk}^3 T_r \exp(-h\nu_{Lk}/kT_r). \quad (5)$$

With the value of  $T_r$  computed with equation (5), using the coronal flux data from Table 1, and values of  $N_e$  and  $T_e$  in the corresponding regions of 304 Å formation, equation (2) can be used to compute the ratio  $R$  of the relative rates for electron collisional excitation and the p-r process.

The mean coronal flux value for  $\lambda < 228$  Å obtained from the Chapman & Neupert (1974) whole Sun values of coronal line emission (of which the values in Table 3 are examples) that follows from applying assumption (2) above is  $5.83 \times 10^4$  ergs cm<sup>-2</sup> s<sup>-1</sup>. Absolute coronal line energy fluxes are obtained from Table 1. Applying assumption (3) then yields an estimate for the local coronal flux below 228 Å for each coronal line in each region identified. Finally, a value of  $T_r$  is obtained for each case with equation (5), from which corresponding values of the ratio  $R$  are computed with equation (2). The results of these computations appear in Table 4.

The results in Table 4 were obtained for the case of  $N_e = 10^{11}$  cm<sup>-3</sup> and  $T_e = 5 \times 10^4$  K. Values for  $N_e$  in the lower transition region will be  $\leq 10^{11}$  cm<sup>-3</sup> in all current models and change slowly with height throughout this region.  $T_e$  is less certain and exerts a much stronger influence on the result, but higher values of  $T_e$  will produce still larger values for the ratio  $R$ . Thus, whenever  $R$  is large compared to unity, we can be

TABLE 4  
COMPUTATIONAL RESULTS<sup>a</sup>

LINE USED TO ESTIMATE LOCAL CORONAL FLUX	VALUE OF RATIO R			
	Quiet Sun	AR Average	Intense AR	Subflare
Mg ix, 368.07 Å .....	1036	91	81	58
Fe xv, 284.16 Å .....	289	33	22	30
Fe xvi, 335.40 Å .....	380	12	8	6(5.6)
Fe xvi, 360.75 Å .....	375	12	8	6(5.6)
GOES data during flare .....	...	...	...	1–2 (1.25–2.49)

<sup>a</sup> Computed values of ratio  $R$  of relative rates of collisional excitation to p-r process, based on intensities of four different strong coronal lines observed with SERTS-3, and on GOES X-ray data obtained for the subflare in AR 5464 that was also observed by SERTS-3. The range of values given for the GOES case corresponds to the range of estimates of the flaring area (see text). Numbers in parentheses give decimal values of computed ratio that are otherwise rounded to nearest integer.

confident that the electron collisional process is dominant, unless collisional excitation occurs with a non-Maxwellian distribution of electrons, which is discussed below.

What can be concluded from these estimates of the ratio  $R$ ? The model of the He II ion we chose for these estimates contains only two bound levels plus the continuum, and the photoionization from the lower level completely dominates that from the upper. Photoionization from additional levels may increase the p-r effect somewhat, so a more complete treatment could reduce the computed value of the ratio, but the effect should be negligible (Avrett, Vernazza, & Linsky 1976). On the other hand, electron temperatures higher than the  $5.0 \times 10^4$  K we assumed will cause the ratio to increase rapidly, and at least in the quiet Sun a large body of work, most recently that of Athay (1988), supports a value of  $T_e$  closer to  $8.0 \times 10^4$  K. Thus our computed values of  $R$  strongly support the findings of many other investigators that electron collisional excitation is the dominant mechanism of 304 Å formation in the quiet Sun. Departures of exciting electrons from a Maxwellian distribution in a higher lying excitation region or excitation in a region of higher electron temperature into which helium might diffuse could improve the agreement between the theoretical intensity of the 304 Å line and observed values under conditions of collisional excitation (Jordan 1975; Shine, Gerola, & Linsky 1976) but would hardly produce a more than two order of magnitude reduction in the ratio  $R$  to allow the p-r process to be competitive in the quiet Sun. In light of all these arguments, the p-r process in the quiet Sun must be regarded as extremely unlikely.

The situation in strong active regions, and especially flaring regions, may be different. This becomes particularly apparent when we estimate a value for  $R$  for a subflare and compare the result (Table 4, fourth column,) to the situation in a region of intense activity (third column) and the quiet Sun (first column). Because the ratio lies generally within the same range as the overestimations of the 304 Å intensity computed under conditions of thermal collisional excitation, it is entirely possible that the coronal radiation in a strong active regime is at least as important as collisional excitation there, although we cannot conclude that this is the case with certainty, both

because of the approximations involved in our method as well as the uncertainty in the values of  $N_e$  and  $T_e$  in the region producing most of the 304 Å radiation.

The trend of the ratio  $R$  from the quiet Sun to a weak flare is very pronounced. From the quiet Sun case, where there is little doubt about collision dominance, to the case of a weak flare, where the p-r mechanism seems sure to compete, and for reasons given above may already be dominant, we see a range of at least two orders of magnitude in the ratio. It is reasonable to conclude that the p-r mechanism will be important, and may be dominant, in strong flares, and probably nonnegligible in weak flares as well.

The trends exhibited in Table 4 also provide some insight into the limitations of the method we have developed for using the SERTS-3 data to estimate the ratio  $R$ . If the method were exact, the value of  $R$  would be the same in each column. Clearly it is not. Nevertheless the same trend is exhibited by all the lines except for one anomaly, the value of  $R$  yielded by the Fe xv 284 Å line for the subflare, which could result from a substantial decrease in the Fe xv/Fe xvi ratio in the subflare. In addition, both from the internal consistency of results from the two Fe xvi lines, which indicates that optical depth effects have yet to compromise the method, as well as from their greater relative change from quiet to active Sun and flare, as one would expect from lines formed at relatively higher coronal temperatures, we conclude that these lines provide the best diagnostic for the relative change in  $R$ , and for its value in the hotter regions at least. However, we note that the value of  $R$  obtained from even these lines is probably an underestimate when very intense XUV radiation arises in a flare. In this latter case, our rough assumption of a linear increase in the coronal radiative flux short of 228 Å with observed line flux has broken down severely, and direct measurements of the XUV radiation are needed.

The authors wish to express their appreciation to Anand Bhatia for calling their attention to the current work in atomic physics that bears on this problem and for checking the derivation of expressions (2)–(5). The flight of SERTS-3 was supported under NASA RTOP 879-11-38.

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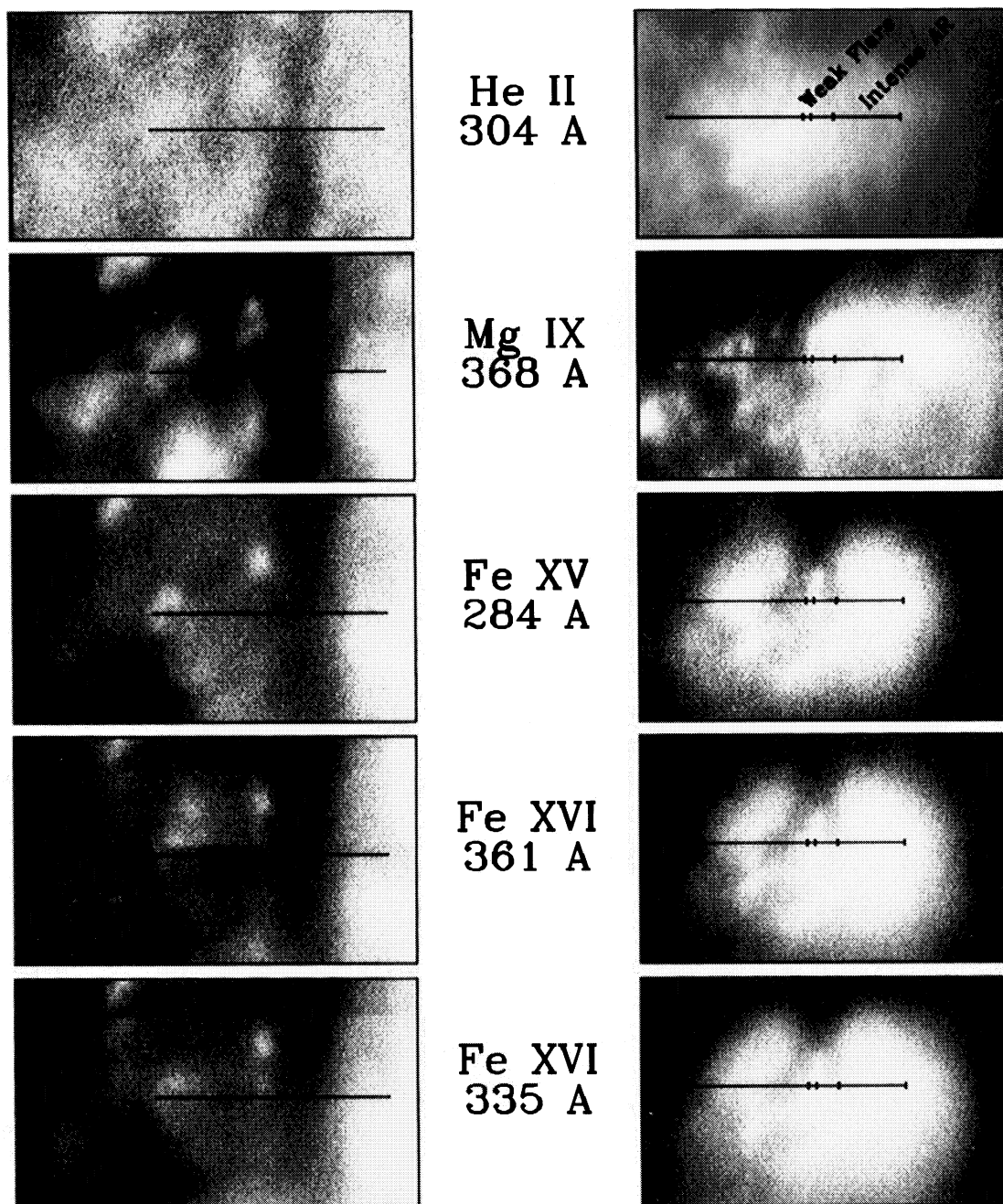


FIG. 1.—Wide-slit images of relatively quiet Sun (*left column*) in five spectral lines observed on 1989 May 5, with SERTS-3, with an exposure time of 256 s; wide-slit images of AR 5464 (*right column*) observed during same flight with an exposure time of 97 s. The location of the narrow slit used to obtain spectra from these same regions is shown on the AR images, along with the portions of the narrow slit over which the intense AR and subflare spectra were averaged. See text for more detailed descriptions.

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